NAVAL HEALTH RESEARCH CENTER

SKIN BLOOD FLOW AND BIOELECTRICAL IMPEDANCE

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Report No. 94-17

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BETHESDA, MARYLAND

Skin Blood Flow and Bioelectrical Impedance[*]

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[*]Report Number 94-17, supported by the Naval Medical Research and Development Command, Department of the Navy, under work unit No. 61152N MR0000.01.01-6041. The views expressed in this article are those of the authors and do not reflect the official policy or position of the Department of the Navy, Department of Defense, nor the U. S. Government. Approved for public release, distribution unlimited.

The authors wish to thank the subjects for their cooperation and dedication, and Ms. Marilyn Reddeg for her editorial assistance.

Summary

Bioelectrical resistance (RES) measured during whole body bioelectrical impedance analysis (BIA) has been used to predict body water and body composition. For accuracy of prediction it is important to identify and control extraneous variables that may influence RES. This study was performed to determine the effect of changes in skin blood flow (SBF) on RES.

Twenty-three men had their left hand repeatedly immersed (1 min) and removed from water (3 min) for a total of 12 min in order to manipulate SBF in the contralateral (right) limbs where RES electrodes were located. Tests were completed at three water temperatures (5, 15, and 35°C) in constant ambient air temperature (25 ± 1°C). SBF was monitored on the middle finger of the right hand using a laser-Doppler flowmeter, and skin temperature on the dorsal right hand (Th) and foot (Tf).

Time series analysis revealed cyclic SBF and RES responses were inversely correlated at all water temperatures ($r = -0.38$ to -0.64; $p < 0.05$). T_h and T_f were not correlated with SBF for any test. ANOVA revealed that changes in RES (+3.5, +2.0, +0.7 Ω) during hand immersion at 5, 15, and 35°C, respectively, differed significantly across all water temperatures, while changes in SBF (-36%, -20%, -4%) differed only between the 5 and 15°C versus the 35°C tests. When incorporated into existing BIA prediction equations, the largest RES difference observed (3.5 Ω) translated into a difference of 0.4% body fat and 0.4 l body water. These results indicate a significant inverse relationship between SBF and RES, however, the magnitude of changes observed in this study appears to have a relatively small impact on BIA prediction of body water and composition.

Introduction

Whole body bioelectrical impedance analysis (BIA) has been used to predict total body water (Davies et al., 1988; Hoffer et al., 1969; Kushner and Schoeller, 1986) and body composition (Jackson et al., 1988; Lukaski et al., 1985,1986; Segal et al., 1985). BIA involves the placement of surface electrodes on the skin of the wrist, hand, ankle, and foot. One pair of electrodes sends an imperceptible alternating current (50 kHz, 800 μA) to the body. The other pair detects the body impedance to that current. Impedance, the resistance to alternating current, has two components: resistance (RES), the direct resistance to current flow, and reactance, the capacitive resistance to current flow. It is the RES component which has been found to be most strongly related to body water content and body composition. Both total body water volume and fat-free mass have been shown to be highly correlated ($r = 0.92$ to 0.98) to the square of body stature divided by RES (Davies et al., 1988; Hoffer et al., 1969; Kushner and Schoeller, 1986; Lukaski et al., 1985,1986).

RES is a function of tissue resistivity, length of the current path, and cross-sectional area of the current path (Baumgartner et al., 1990). Tissue resistivity in biological substances is related to electrolyte concentration, that is, both the electrolyte content and the volume within which the electrolyte is distributed (Baumgartner et al., 1990). Tissues with low electrolyte content, such as bone and fat, have relatively high resistivity (Pethig, 1979). Muscle and blood, the major components of the fat-free mass, have a high electrolyte content, relatively low resistivity, and comprise the major current paths within the body (Baumgartner et al., 1990). In fact, blood has one of the lowest resistivities of any of the body tissues (Pethig, 1979).

In performing BIA on humans, efforts have been made to control extraneous variables that might influence the relationship between RES and body water or fat-free mass. Common pretest preparations are designed to produce a euhydrated, fasted, nonperspiring subject with normal body temperature (Helenius et al., 1987; Lukaski et al., 1986). Body posture and electrode placement are also standardized. Effects of ambient temperature on BIA have been demonstrated by Caton et al. (1988). In their study, subjects were measured for RES and skin temperature of the hand and foot under warm conditions (35°C) and with the room cooled to 14°C. RES was observed to increase significantly from 426 to 461 Ω while skin temperature decreased

significantly from 33 to 24°C. These investigators speculated that changes in RES might be due to fluid shifts or alterations in skin blood flow (SBF) induced by the change in ambient temperature. In an effort to examine the effect of SBF and skin temperature on BIA, Liang and Norris (1993) tested men prior to and after an exercise bout. They observed a significant increase in SBF and skin temperature, but no change in RES.

One method of altering SBF without changing ambient air temperature or exercising is immersion of the hand or foot into cold water. Previous studies have shown that this results in a reduction of SBF in the immersed hand or foot (LeBlanc, 1975; Spealman, 1945), and also in the contralateral limbs (Rosén et al., 1988; Zbrozyna, 1982) . In the present study, repeated cycles of cold water hand immersion were used to alter SBF in the contralateral limbs where BIA electrodes were located.

A relatively new technology for measuring SBF is laser-Doppler flowmetry. A low-power, helium-neon laser beam is used to penetrate a small hemisphere of skin having a radius of 1 to 1.5 mm. Light striking moving blood cells is reflected with a shift in frequency and is analyzed to determine cell flux, i.e., relative blood flow. Previous investigators have shown that laser-Doppler flowmetry provides a valid measurement of blood flow through superficial capillaries and arteriovenous anastomosis of the skin and is well-suited to measuring perfusion reaction to a stimulus, i.e., changes in perfusion (Engelhart and Kristensen, 1983; Hirata et al., 1988).

The purpose of the present investigation was to determine the effect of changes in SBF on RES in resting subjects under conditions of constant ambient air temperature.

Methods

<u>Subjects</u>.

Subjects in this study were 23 healthy men who gave informed consent and reported to the laboratory at the same time on three different days. Study design was approved by the Committee for Protection of Human Subjects at the Naval Health Research Center. Subjects complied with instructions designed to place them in a euhydrated, nonperspiring, normal body

temperature state. They refrained from exercise, eating or caffeine for three hours prior to their appointment. Alcohol was not consumed in the 12 hours prior to testing. Drinking of fluids was allowed up to one hour prior to testing. At the beginning of each test session, subjects emptied their bladders.

Hand Immersion Test.

Each subject underwent hand immersion tests at three different water temperatures, 5, 15, and 35°C, which were administered in counterbalanced order on separate days. The 35°C test was used to examine the effects of hand movement and water immersion without a cold stimulus. In each test, the left hand was immersed and all measurements of SBF, RES, and skin temperature were taken on the right hand and foot.

Each hand immersion test was preceded by a 20-min stabilization period to allow completion of fluid shifts associated with assuming a supine position (Hagan et al., 1978), and to ensure that measured parameters reached a steady state. The 12-min hand immersion test consisted of three cycles of a 1-min hand immersion with a 3-min recovery. Subjects were supine and immobile (except for left hand and forearm) throughout the experiment (Figure 1). Subjects were covered by a light sheet and room temperature was maintained at 25°C (± 1°C). Because talking appeared to affect SBF, subjects refrained from speaking during the experiment. At the beginning of each immersion, the subject's left hand was guided into a circulating water bath (Fisher Scientific 730-13R, Tustin, CA) held at constant temperature (± 0.1°C). At the conclusion of the immersion period, the hand was guided back to the resting platform. Because of careful arm and hand positioning, hand immersion and removal were accomplished with no movement above the elbow.

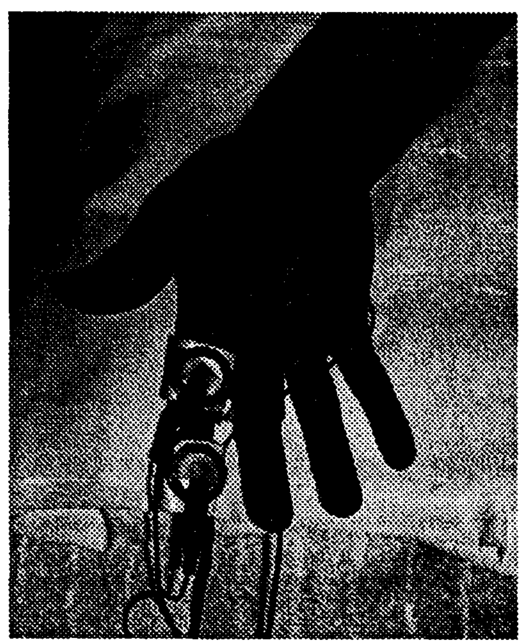
Skin Blood Flow.

SBF at the finger was measured continuously with a laser-Doppler flow meter (Perimed PF3, Piscataway, NJ) using a PF314 probe on the second finger of the right hand, centered on the palmar surface of the proximal phalange and held in place with an adhesive-backed disk (Figure 2). The SBF voltage signal was input to a VAXlab computer (Digital Equipment Corp., Maynard, MA), sampled 50 times per second, and averaged over 15-sec intervals to provide the values that were displayed and recorded. Although the voltage signal itself is well-suited for

(a) (b)

Figure 1. Subject position during testing: (a) left hand resting on platform above water bath; (b) left hand immersed. Note: all measuring electrodes are located on right hand and foot.

Figure 2. Bioelectrical resistance electrodes on index finger and skin blood flow probe on middle finger.



assessing changes in SBF, it cannot be expressed in physiological units, such as ml of blood per ml of tissue, because the same blood flow, defined in these units, will yield a different flow meter signal in different kinds of tissue (manufacturer's handbook).

In preliminary work, measurement of SBF on the dorsal aspect of the hand was evaluated because it was midway between the normal wrist and hand electrode sites used in BIA. SBF at this site, however, was deemed insufficient for the design of this study. The finger site described above was chosen because 1) its blood flow was approximately four times that of the back of the hand; and 2) BIA electrodes could be relocated so that the detecting electrode was placed in an equivalent position on the index finger. In order to test the hypothesis that SBF measured at the second finger was equivalent to SBF at the index finger (under the BIA electrode), each subject had SBF measured at rest at each site, with the order of measurements counterbalanced. No difference ($p > 0.05$) in SBF at the two sites was found.

Bioelectrical Resistance.

Prior to the first immersion test, a standard assessment of whole body resistance was made using the BIA-101A analyzer (RJL Systems, Detroit, MI) according to guidelines provided by the manufacturer. During the immersion tests, BIA electrode sites on the foot and ankle were as described by the manufacturer, but hand sites were located on the finger because SBF was being monitored at the finger. The sending and detecting electrodes were placed on the index finger, on the palmar surface of the distal and proximal phalanges, respectively (Figure 2). Skin sites were cleansed with alcohol and allowed to dry prior to application of pregelled, adhesive spot (EKG) electrodes. For the finger sites, the adhesive pads were trimmed so that the gel spots could be placed at least 4 cm apart. These particular electrodes were used because in preliminary studies they were found to provide constant RES during 45 minutes of steady state measurement. In contrast, the gummed, foil-type electrodes provided by the manufacturer yielded steadily increasing RES under these same conditions. RES values displayed at the BIA meter were visually averaged and recorded for the last 15-sec of each minute of the stabilization period and for each 15-sec interval of the 12-min immersion test.

Skin Temperature.

YSI 409B thermistors and 43TA tele-thermometers (Yellow Springs, OH) were used to measure skin temperature at the center of the dorsum of the right hand (T_h) and foot (T_f), the same sites used by Caton et al. (1988). Skin temperatures were recorded via computer in the same manner as described for SBF.

Treatment of Data.

Time series analysis (Bendat and Piersol, 1966) was used to reveal the degree of association between SBF and RES, T_h, or T_f responses. In this type of analysis, a set of observations on two variables over a series of time points is cross-correlated. An in-house developed FORTRAN program using the Pearson product moment correlation coefficient (Schefler, 1979) was used to perform cross-correlation on each subject's raw data. Cross-correlations were calculated with no lag and at 16 progressive lag intervals (15, 30, 45 ... 240 sec) to determine if there was a response delay. As an example, the 15-sec lag was achieved by cross-correlating each SBF data point with the RES data point that occurred 15 sec later.

Baseline RES and SBF were calculated as the average first preimmersion value across all three tests. Average change scores for SBF and RES were calculated for each test in the following way. For each data point collected during hand immersion, the difference between SBF (or RES) and the preimmersion value for that particular immersion was calculated. Differences were then averaged across all immersions within each test to produce the average change score. This change score is proportional to the area under the response curve during immersion. Repeated measures ANOVA and post hoc t-tests (SPSS Inc., 1986) were used to determine if change scores differed across water temperatures and to detect differences in T_h and T_f pre- and postimmersion, and from beginning to end of test. In all analyses, significance was accepted at $p < 0.05$.

Results

Subject characteristics are presented in Table 1. One subject had one missing RES value in each of the three tests, and another subject had one missing RES value in the 35°C test. These missing values were replaced with the average of the immediately preceding and following RES values.

TABLE 1. Subject characteristics (n = 23).

	Mean	SD
Age (yr)	30.5	7.75
Height (cm)	178.8	7.32
Weight (kg)	83.5	15.18
%Fat[a]	18.6	6.75
Standard Resistance (Ω)[b]	442.1	51.8
Baseline Resistance (Ω)[c]	670.8	77.1
Baseline Skin Blood Flow (V)[c]	0.334	0.152

[a] %Fat calculated from circumferences and height (Hodgdon and Beckett, 1984).
[b] Whole body resistance with standard electrode placement.
[c] Under test conditions, during preimmersion stabilization period.

Mean group SBF and RES responses at each of the three water temperatures are plotted in Figure 3. Time series analysis of individual SBF and RES responses revealed significant ($p < 0.05$) inverse cross-correlation at all three water temperatures (Table 2). The largest correlation coefficients were achieved at lags of less than 60 sec. Individual variation was large; for example, at 5°C and using a 15-sec lag, the individual correlations ranged from -0.12 ($p > 0.05$) to -0.89 ($p < 0.001$).

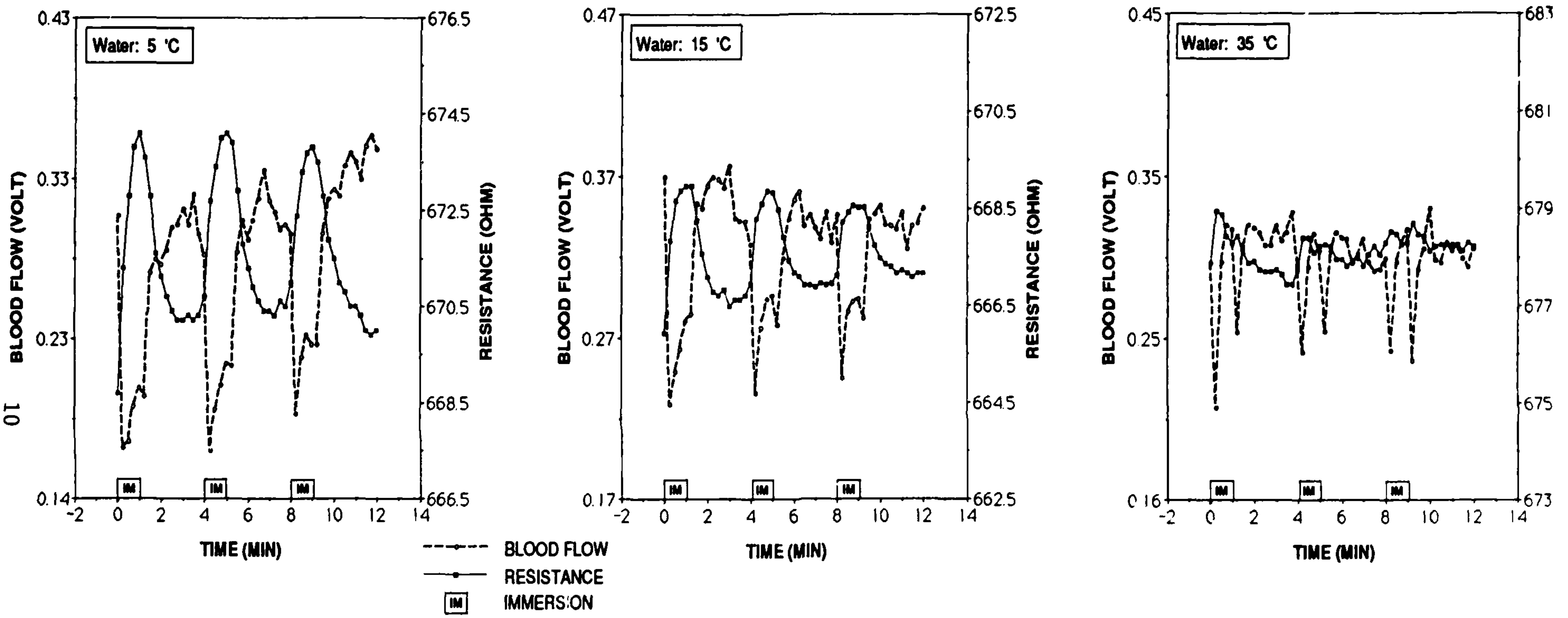


Figure 3. Mean group (n = 23) skin blood flow and bioelectrical resistance responses to repeated hand immersion in water at 5, 15, and 35 degrees C. Scales used for the three graphs are equivalent.

TABLE 2. Time series analysis of skin blood flow and bioelectrical resistance responses of individuals (n = 23).

Water Temperature (°C)	Lag Time (sec)	Cross-correlation Mean	SD
5	0	-0.59^{***}	0.24
	15	-0.64^{***}	0.22
	30	-0.57^{***}	0.20
	45	-0.45^{**}	0.17
	60	-0.30^{*}	0.15
15	0	-0.47^{***}	0.23
	15	-0.46^{***}	0.23
	30	-0.39^{**}	0.25
	45	-0.33^{*}	0.20
	60	-0.25	0.18
35	0	-0.38^{**}	0.17
	15	-0.31^{*}	0.17
	30	-0.19	0.17
	45	-0.15	0.21
	60	-0.17	0.21

At a lag of 0, the cross-correlation was derived from 49 pairs of data for each subject. At each successive lag, the number of data pairs was reduced by one.

* $p < 0.05$
** $p < 0.01$
*** $p < 0.001$

TABLE 3. Hand and foot skin temperatures.

Skin Temperature (°C)		Water Temperature 5°C Mean	5°C SD	15°C Mean	15°C SD	35°C Mean	35°C SD
Hand							
1st Immersion	Pre	33.88	1.28	34.07	0.98	34.13	1.26
	Post	33.83[a]	1.28	34.04	0.97	34.11	1.24
2nd Immersion	Pre	33.78	1.26	34.06	0.96	34.12	1.22
	Post	33.74[a]	1.25	34.04	0.96	34.12	1.21
3rd Immersion	Pre	33.73	1.25	34.06	0.97	34.14	1.19
	Post	33.71[a]	1.25	34.05	0.96	34.14	1.18
End Test		33.74[b]	1.26	34.07	0.97	34.15	1.16
Foot							
1st Immersion	Pre	32.10	1.29	32.12	1.19	32.15	1.35
	Post	32.12	1.29	32.09	1.17	32.13	1.36
2nd Immersion	Pre	32.03	1.27	32.10	1.18	32.21	1.35
	Post	32.00	1.25	32.09	1.16	32.22	1.35
3rd Immersion	Pre	31.96	1.26	32.13	1.18	32.25	1.35
	Post	31.95[b]	1.26	32.11	1.19	32.27	1.35
End Test		32.00	1.26	32.13	1.21	32.31[b]	1.34

n = 23, except for hand temperature during 15°C test, in which n = 22
[a]Significant ($p < 0.05$) difference between pre- and postimmersion values.
[b]Significantly ($p < 0.05$) different from 1st preimmersion value.

Time series analysis of skin temperature and SBF revealed no significant cross-correlations at any lag interval. ANOVA and post hoc t-tests revealed several significant ($p < 0.001$), but small (≤ 0.16°C), decreases in T_h and T_f during the 5 and 35°C tests (Table 3).

Average change in SBF and RES during the 1-min hand immersion periods is reported in Table 4. ANOVA revealed a significant water temperature effect on the average change in both SBF and RES ($p < 0.001$). Post hoc t-tests showed the change in RES to be different ($p < 0.001$) at each water temperature, while the change in SBF was different ($p < 0.01$) only between the cold water (5 and 15°C) and 35°C immersions. In terms of relative change, RES increased by less than 1% from the preimmersion value, but SBF decreased by up to 36%.

TABLE 4. Average change in skin blood flow and bioelectrical resistance during hand immersion periods (n = 23).

Water Temperature	ΔBlood Flow (V)[a]	ΔResistance (Ω)[b]
5	-0.11 ± 0.052 (-36%)	3.5 ± 1.76 (+0.5%)
15	-0.08 ± 0.080 (-20%)	2.0 ± 1.55 (+0.3%)
35	-0.02 ± 0.048 (-4%)	0.7 ± 0.67 (+0.1%)

Values (mean ± SD) reflect the average change occurring during three 1-min hand immersions at each temperature. Values in parentheses are percent change from the preimmersion value.

[a] Significant ($p < 0.01$) differences between all blood flows except between 5 and 15°C.
[b] Significant ($p < 0.001$) differences between all resistance values.

Discussion

In this study, SBF was manipulated by repeated hand immersion in cold water in order to evaluate possible associated changes in bioelectrical RES. Time series analysis revealed significant cross-correlation between SBF and RES. Cyclic changes in SBF were inversely related to cyclic changes in RES. RES may lag behind SBF, but the response time appears to be less than 30 sec.

The most pronounced SBF and RES responses were seen in the 5 and 15°C tests (Figure 3). Responses were also observed, however, during the supposedly thermo-neutral 35°C test. In that test, transient reductions in SBF occurred at points of hand immersion and removal. Rosén et al. (1988) reported that when an extremity is lowered, local SBF is reduced by a reflex vasoconstriction brought about by increased venous pressure in the extremity. The transient reductions in SBF seen in the 35°C test may be due to this reflex vasoconstriction. If so, our study indicates that these reflexes occur not only locally, but also in the contralateral extremity, and they occur in response to both lowering and raising of an extremity. The low, but significant, negative correlation between SBF and RES during the 35°C test indicates that these transient drops in SBF were accompanied by some increase in RES. Because of the short duration of the SBF response, however, average change in RES during 35°C immersion is very small compared to RES changes seen in the cold water tests. These findings indicate that changes in RES observed during cold water immersion are not due simply to the slight position change associated with hand immersion, but are directly related to cold-induced vasoconstriction. These findings are supported by a previous study in which an inverse correlation between SBF and RES was observed during exercise-induced vasodilation (Liang and Norris, 1993).

T_h and T_f changed by less than 1%, despite alterations of up to 36% in SBF. Interpretation of these results is difficult because of the different sites used for measurement of SBF (finger) and skin temperatures (dorsal hand and foot). Previous research has shown a direct relationship between skin temperature and perfusion in the finger, but not in the hand, forearm, foot, and calf (Stoner et al., 1991). Rosén et al. (1988), however, reported that a significant decrease in finger SBF was accompanied by no change in finger skin temperature during 1 min of contralateral hand cooling in 4°C water. It is possible that 1-min hand immersions are too

brief to elicit much change in skin temperature in the contralateral hand. Therefore, even if SBF and T_h had been monitored at adjacent sites, it is unclear whether or not a substantially different relationship between SBF and skin temperature would have been observed.

The 36% average decrease in SBF seen in the 5°C test is in agreement with Rosén et al. (1988), who reported a 38% median reduction in finger SBF during 1 min of contralateral hand immersion in 4°C water. Accompanying the 36% reduction in SBF seen in the present study, there was an average increase in RES of 3.5 Ω. In practical applications where RES is used to estimate body composition or total body water, this magnitude of change in RES would have a relatively small effect. For example, a 4 Ω increase in the total body resistance of a man with the physical characteristics of the mean of our sample would result in an increase of about 0.4% in predicted body fat and a decrease of about 0.4 liters in predicted total body water using the BIA analyzer manufacturer's equations. Thus, under the conditions of vasoconstriction induced in this study, changes in SBF appear to have a relatively small impact on bioelectrical prediction of body water and body composition. Similarly, Liang and Norris (1993) have reported no significant change in RES during a bout of moderate exercise, despite a three-fold increase in SBF and a small increase in skin temperature (< 2°C).

Caton et al. (1988), however, did observe a relatively large change in RES (35 Ω) during experiments in which subjects were monitored while ambient temperature was lowered from 35 to 14°C over a 90-min period. The 3.5 Ω change in RES seen in the present study is one-tenth of the magnitude of the change reported by Caton et al. Perhaps this discrepancy can be explained by looking at other differences between the two studies. In the present study, ambient temperature was constant and there was minimal change in hand and foot skin temperature ($\leq$ 0.16°C). In the experiment of Caton and coworkers, however, ambient temperature was lowered by 21°C and skin temperature of the hand and foot decreased by 9°C. That large change in skin temperature may have been associated with a relatively large change in SBF, one of greater magnitude than was induced in the present study or in the vasodilation study of Liang and Norris (1993). In addition, in the Caton et al. study, changes in the temperature of the skin itself and other physiological changes associated with body heating and cooling, such as perspiration and fluid shifts, may have further affected RES.

As was stated earlier, insufficient SBF on the dorsal hand (under thermo-neutral conditions) made monitoring both SBF and RES at the standard BIA hand sites infeasible; therefore, the fingers were chosen as an alternative site where both variables could be monitored. Baseline RES obtained with electrodes on the index finger was 50% greater than the resistance measured with the standard electrode placement. This finding may be due to the smaller cross-sectional area of the finger relative to the wrist. It is known that the smallest cross-sectional areas within the BIA current pathway primarily determine the resistance (Baumgartner et al., 1990). Although RES measured with the finger sites is not equivalent to that measured with the standard electrode placement, the results of the present study clearly identify the relative alterations in RES that accompany vasoconstriction from the thermo-neutral condition.

Conclusion

In this study, SBF and RES responses were found to be significantly and inversely related. Under the conditions of vasoconstriction induced in this study, relatively small changes in BIA-based predictions of body water (-0.4 l) and percent body fat (+0.4%) were observed.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
June 14, 1994

3. REPORT TYPE AND DATE COVERED
Final Jul89-Sep90

4. TITLE AND SUBTITLE
Skin Blood Blood Flow and Bioelectrical Impedance

5. FUNDING NUMBERS
Program Element: 61152N
Work Unit Number: MR00001.01

6. AUTHOR(S) Marcie B. Beckett, James A. Hodgdon, Wanda Woods, Brian W. Appleton

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Health Research Center
P. O. Box 85122
San Diego, CA 92186-5122

8. PERFORMING ORGANIZATION
Report No. 94-17

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Naval Medical Research and Development Command
National Naval Medical Center
Building 1, Tower 2
Bethesda, MD 20889-5044

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This study was performed to determine the effect of changes in skin blood flow (SBF) on bioelectrical resistance (RES). Twenty-three men had their left hand repeatedly immersed (1 min) and removed from water (3 min) for a total of 12 min in order to manipulate SBF in the contralateral (right) limbs where RES electrodes were located. Tests were completed at three water temperatures (5, 15, and 35°C) in constant ambient air temperature (25 ± 1°C). SBF was monitored on the middle finger of the right hand using a laser-Doppler flowmeter, and skin temperature on the dorsal right hand (Th) and foot (Tf). Time series analysis revealed cyclic SBF and RES responses were inversely correlated at all water temperatures ($r = -0.38$ to -0.64; $p < .05$). T_h and T_f were not correlated with SBF for any test. During hand immersion in 5, 15, and 35°C water, SBF decreased by 36, 20, and 4%, respectively, while RES increased by 3.5, 2.0, and 0.7 ohms, respectively. When incorporated into existing bioimpedance (BIA) prediction equations, the largest RES difference observed (3.5 ohms) translated into a difference of 0.4% body fat and 0.4 L body water. Changes in SBF of the magnitude observed in this study appear to have a relatively small impact on BIA prediction of body water and composition.

14. SUBJECT TERMS
Bioelectrical impedance, skin blood flow, body composition, skin temperature, laser-Doppler flowmetry

15. NUMBER OF PAGES
18

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited